In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institute shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

3/17/65
b

THE THERMAL CONDUCTIVITY OF BEEF

A THESIS

Presented to

The Faculty of the Graduate Division

by

James Edward Hill

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

March, 1966

THE THERMAL CONDUCTIVITY OF BEEF

Approved:

Chairman

Date approved by Chairman: 3/4/66

ACKNOWLEDGMENTS

The author is deeply indebted to many people who made this work possible. First of all, he would like to thank Dr. J. E. Sunderland, his advisor, who gave many hours of willing advice and encouragement during all phases of this investigation. He would like to thank Dr. A. B. Huang and Professor W. A. Hinton for their service on the reading committee. Also the author is appreciative of the assistance given by Mr. C. R. Bannister and Mr. L. A. Cavalli in the fabrication of the experimental apparatus and the assistance given by Mr. Dave Colley in the experimental portion of this investigation.

The author would like to express his gratitude for the Public Health Research Grants EF 00102-02 and EF 00102-03 from the Division of Environmental Engineering and Food Protection and for a summer fellowship from the National Science Foundation which provided partial support for this investigation.

Finally, it would be impractical here for the author to thank all the members of his family who have helped him in his educational endeavors. However, he would like to acknowledge his debt to his grandmother, Mrs. J. M. Hill, who recently passed away. Her guidance and encouragement during his early life were instrumental in formulating his educational goals.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

An apparatus was constructed to measure the thermal conductivity of nondehydrated beef. Measurements were made on frozen and fresh beef in the temperature range 0 to 50°F. The samples were taken from the inside round of canner and cutter grade beef. The data were obtained in order to show the dependence of conductivity on temperature, moisture content, and direction of heat flow (perpendicular or parallel to the grain of the beef).

The method used was based on one-dimensional steady heat flow through the sample. The samples were 9 inch square slabs 1 inch thick and were placed between two copper plates. The plates were of uniform temperature and differed by approximately 30 degrees. The plates' temperatures were controlled separately by passing ethylene glycol solutions at constant temperature through copper coils which had been soldered to the back of these plates. A differential thermopile was used to measure the temperature difference across the sample, and a specially constructed heat meter was placed with the sample between the "hot" and "cold" plates to measure the rate of heat transfer through the sample. The entire assembly was surrounded by insulation and enclosed in polyethylene. Fourier's one-dimensional heat conduction equation was used to calculate the thermal conductivity.

Measurements were made on one sample with the heat flow parallel to the grain of the meat and on one sample with the heat flow perpendicular to the grain. The moisture content was nearly the same for both samples.

It was found that in the frozen region (0 to 22°F), the sample measured parallel to the grain had a conductivity 16 percent higher than the sample measured perpendicular to the grain. For both samples, the conductivity varied inversely with temperature in the frozen region and was directly proportional to the temperature in the unfrozen region. When comparing the data with data of previous investigations, it could be seen that the conductivity would be higher for samples with higher water contents. The conductivity values for the sample measured perpendicular to the grain varied from 0.647 to 0.583 Btu/hr ft°F in the temperature range 8 to 25°F and varied from 0.252 to 0.257 Btu/hr ft°F in the temperature range 36 to 46°F. The conductivity of the sample measured parallel to the grain varied from 0.796 to 0.690 Btu/hr ft°F in the temperature range 0 to 22°F and varied from 0.230 to 0.232 in the temperature range 37 to 47°F.

The conductivity values of the sample measured parallel to the grain were compared with values that were predicted by a previously proposed model. The model predicted the conductivity as a function of moisture content for lean beef with a moisture content of 60 percent or higher, where the heat flow was parallel to the grain. The values compared very well in the frozen region with the predicted values. The greatest difference was 3 percent. This model can certainly be a valuable tool in the analytical work of freeze-drying.

NOMENCLATURE

English Letters		Units
A	area	ft^2
a	constant	Btu/hr ft °F
b	constant	Btu/hr ft $°F^2$
c	constant	Btu/hr ft $°F^3$
c_ρ	constant pressure specific heat	Btu/lbm °F
d	constant	°F
e	constant	°F/ft
f	constant	$°F/ft^2$
g	constant	°F
h	constant	°F/hr
i	constant	$°F/hr^2$
k	thermal conductivity	Btu/hr ft °F
q	heat flow rate	Btu/hr
Q	heat flow rate per unit length of cylinder	Btu/ft hr
r	radial distance	ft
t	temperature	°F
x	distance coordinate	ft

Greek Letters		
α	thermal diffusivity	ft^2/hr
β	dummy variable	
ρ	density	lbm/ft^3
τ	time	hr

CHAPTER I

INTRODUCTION

Statement of Intent

It is the intention of this study to design and construct equipment for the measurement of thermal conductivity of beef. The equipment will be used to measure the conductivity of several samples of non-dehydrated beef in order to study the dependence of the property on temperature, moisture content, and direction of heat transfer (parallel or perpendicular to the grain of the fiber).

Purpose

The thermal conductivity of beef is a very important property which is needed for analytical studies of transient processes where beef is heated, cooled, or dehydrated as in the freeze-drying process. Engineering design of freeze-drying equipment for food processing has been hampered by a lack of fundamental information of the properties of food, such as thermal conductivity.

The freeze-drying process is basically the following: a product is frozen and then placed in a vacuum chamber which is evacuated to a pressure lower than the triple point of ice. The product is heated and the water or water substance in the product sublimes and passes out of the product. The determination of conductivity will result in a better understanding of the heat transfer problem involved in the freeze-drying process.

In the past few years there has been increasing interest in freeze-drying both in the laboratory and on the commercial level. Laboratory investigations have been going on since about 1945, but as recently as 1960 there were only two major food processors marketing freeze-dried foods in the United States. At present, there are at least 20 major processors engaged in this field (17). It has been estimated that the sale of freeze-dried food could reach two billion dollars by 1970 (18).

There are very few substances that are as important in this area as beef. However, the data available on beef are by no means complete (Appendix A). There are only two sets of data that have been reported for beef where the conductivity has been measured perpendicular to the grain as a function of temperature (Lentz (6) and Cherneeva (4)). These sets of data were taken on samples with different moisture contents and additional data at still other moisture contents will certainly increase the understanding of the dependence of the conductivity on water content. In the freeze-drying process, beef is always dried so that the heat flow and vapor flow are parallel to the grain because of the faster drying time. Here again, only two sets of data are available for conductivity of nondehydrated beef measured parallel to the grain as a function of temperature. The data reported (Lentz (6) and Miller (7)) differs by as much as 30 percent with a moisture content difference of only 5.5 percent. Miller (20) presents a model for the calculation of conductivity of beef parallel to the grain as a function of water content that is in excellent agreement with his data, but predicts values 11 percent below Lentz's data. It is felt that additional data to check the validity of this model will certainly be beneficial to the analysis of the freeze-drying of beef.

It is very difficult to compare data reported by different investigators due to the different types of apparatuses used and the various kinds of beef available. Only one investigator (Lentz) has made simultaneous measurements perpendicular and parallel to the grain. This will be done in this investigation in hopes of furthering the understanding of the dependence of the conductivity on heat flow direction.

CHAPTER II

METHODS OF MEASURING THERMAL CONDUCTIVITY

Before the present method of measuring the thermal conductivity was adapted, an extensive survey was made of methods previously used. It would be highly impractical to discuss all the methods that have been used in the past, so this chapter will be devoted to several of the more interesting approaches to the problem.

Transient Method - Shenhav

This method, described by Shenhav (10) as the one he used on insulating materials, is based on the one-dimensional, unsteady heat conduction equation:

$$\rho \ c_p \ \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x} \left(k \left(\frac{\partial t}{\partial x}\right)\right) \tag{1}$$

where k is considered a function of temperature. The equation can also be written:

$$\rho \ c_p \frac{\partial t}{\partial \tau} = k \frac{\partial^2 t}{\partial x^2} + \frac{\partial k}{\partial t} \left(\frac{\partial t}{\partial x}\right)^2 \tag{2}$$

He assumes that the conductivity can be accurately represented for insulating materials by a polynomial expansion:

$$k = a + bt + ct^2 \tag{3}$$

Equation (2) now becomes:

$$\rho \ c_\rho \frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial x^2} + b \left[\left(\frac{\partial t}{\partial x}\right)^2 + t \frac{\partial^2 t}{\partial x^2} \right]$$

$$+ c \left[2t \left(\frac{\partial t}{\partial x}\right)^2 + t^2 \frac{\partial^2 t}{\partial x^2} \right] \tag{4}$$

If a slab of insulation with a uniform temperature has the surface temperature instantaneously changed, a one-dimensional transient situation exists in which the temperature in the insulation is a function of time and distance from the hot surface. Shenhav assumes that the temperature distribution at a particular time can be expressed by:

$$t = d + ex + fx^2 \tag{5}$$

where x is the distance from the hot surface. Also at a given distance from the surface, he assumes that the transient temperature can be approximated by:

$$t = g + h\tau + i\tau^2 \tag{6}$$

The coefficients d, e, and f are evaluated by measuring the temperature at three specific points in the sample. The coefficients g, h, and i are determined by temperatures of one point in the sample measured at three different times. Three sets of measured values of t and values of $\frac{\partial t}{\partial \tau}$, $\frac{\partial t}{\partial x}$, and $\frac{\partial^2 t}{\partial x^2}$ derived from equations (5) and (6) are used in solving equation (4) for the values of the coefficients a, b, and c. The values of a, b, and c are substituted into equation (3) giving an expression for the conductivity as a function of temperature valid in the range of temperature data taken.

The apparatus used by Shenhav consisted basically of an electrically heated hot plate on which the insulation sample was placed and a multipoint millivolt recorder used to record the temperature time relationship. Thermocouples were threaded in the sample for the temperature sensing, and their distances from the hot surface were measured by cutting the sample open after completion of the test, which lasted approximately four minutes. Results were reported for tests on a fiberglas insulation sample to be within 2.2 percent of the published values.

The method seemed to work well for insulating materials and it seemed reasonable to assume that it could be adapted for measurements on beef or other substances in which the conductivity varies similarly to insulation. During the first part of the period covered by this research, an attempt was made to duplicate the method, using the same type equipment as well as a computer program to solve the equations. When the same type of insulation as Shenhav used was employed in this study to check the accuracy, no meaningful data were obtained. At present, no explanation has been found for this discrepancy.

Method for Poor Conductors - Zierfuss (11)

The theoretical case of two semi-infinite bodies of different temperatures which are held in ideal thermal contact was considered. It can be shown mathematically that the temperature at the interface immediately acquires a value given by:

$$\frac{t_1 - t_i}{t_1 - t_2} = \frac{k_2/\alpha_2^{1/2}}{k_1/\alpha_1^{1/2} + k_2/\alpha_2^{1/2}} \qquad (7)$$

The subscripts 1, 2, and i refer to the hot body, cold body, and the interface respectively. For a short time, marked temperature changes are limited to regions close to the interface; in other words, small bodies behave rather like semi-infinite bodies during this period. Zierfuss used small rock samples as cold bodies; brought them into contact with a hot body of known thermal properties and t_1, t_2, t_i were measured. It was thus easy to find $k_2/\alpha_2{}^{1/2}$ for the sample by means of equation (7) or a calibration curve. Knowing the specific heat and density of the sample, k could then be determined.

The experimental set up used by Zierfuss consisted of a copper U-shaped capillary of about 10 cm in length and 8 mm in diameter. An electrical heater was used to bring the capillary to the desired initial temperature t_1. The capillary contained a low melting alloy which was in the liquid state during the measurements. The alloy protruded somewhat from the left end of the U-tube when no sample was present, but was forced into the capillary when a sample was put in place. In this way a good thermal contact was insured, and a steady interface temperature was reached in about 30 seconds. The samples were stored in a wooden box at a uniform temperature t_2, which was about room temperature. Thermocouples were used to measure the necessary temperatures and a potentiometer circuit was devised to read $t_1 - t_i/t_1 - t_2$ directly.

Although Zierfuss reported an accuracy to within 5 percent, he found that the heat flow through the samples deviated a great deal from the theoretical case of one-dimensional linear heat flow. The radial heat flow component seemed to have an effect, especially for relatively better conductors. It was felt that this method could not easily be adapted for measurements on beef due to the definite difference in conductivity parallel and perpendicular to the grain of the meat, as well as needing the specific heat of each sample tested.

Guarded Hot Plate Method (12)

No discussion of conductivity methods would be complete unless a description of this method were included. It is the standard of the American Society for Testing Materials for materials having conductivities not in excess of 0.4 Btu/ft hr °F.

For steady one-dimensional heat flow through a slab with fixed boundary temperatures t_1 and t_2, $t_1 > t_2$, the general heat conduction equation becomes:

$$\frac{d^2t}{dx^2} = 0 \qquad (8)$$

The solution of this equation with the boundary conditions applied takes the form:

$$t = t_1 + \frac{t_2 - t_1}{x_2 - x_1}(x - x_1) \qquad (9)$$

The rate of heat flow through the slab may be found from Fourier's basic law of heat conduction:

$$q = -k\ A\frac{dt}{dx} \qquad (10)$$

Introducing $\frac{dt}{dx}$ from equation (9),

$$q/A = k\ \frac{t_1 - t_2}{x_2 - x_1}$$

or

$$k = q/A \, \frac{x_2 - x_1}{t_1 - t_2} \tag{11}$$

This equation is valid for constant conductivity. For the case where the conductivity is a linear function of temperature, the equation is still valid but the conductivity k now is the conductivity of the material at the average temperature $\frac{t_1 + t_2}{2}$. For most applications where the conductivity varies with temperature, it can be assumed to vary linearly over the temperature range t_1 to t_2.

The standard apparatus consists of a central resistance heater, two unknown but identical samples, and two cooling plates on the other sides of the samples. The central resistance heater has around it a small air gap and then another heater kept at the same temperature as the central heater. This is to insure that all the energy given off by the central heater passes through the samples. The cold plates are usually metallic and cooled by a fluid. The central heater energy, the distances across the samples, and temperature drops across the samples are measured. Equation (11) is then used to calculate the conductivity.

This method is quite accurate but has the disadvantage of requiring a great amount of time, perhaps several days to obtain one measurement.

Thin Heater Method

Hager (13) describes a variation on the guarded hot plate method. The heater used is a rectangular sheet of stainless steel foil. Sample slabs are placed against opposite sides of the heater and the combination is enclosed in a plastic bag and immersed in a bath having constant and uniform temperature. Differential thermocouples are used to measure the temperature drop across the samples. Equilibrium is reached in 15 minutes and an accuracy of 2 percent is estimated.

Method of Schröder (14)

This method, like the guarded hot plate method, is based on Fourier's steady one-dimensional heat conduction equation. Two ends of a cylindrical sample about 18 mm in diameter and from 0.5 to 30 mm in length are kept at constant temperatures, by contact with two boiling liquids with suitable boiling points, differing by approximately 20°F. The time is measured in which a quantity of heat flows through the sample. The quantity of heat is measured indirectly by calculating the amount of heat required to evaporate a certain amount of the liquid at the "cold end" of the sample, which is collected as condensate.

Schröder applied the method by measuring two calibrated samples first and plotting a calibration curve from which the thermal resistance of subsequent samples could be found. It was not necessary for him to know the exact boiling points of the two liquids, nor the absolute amount of evaporated liquid, nor its heat of vaporization. A measurement took 5 to 15 minutes and he reported that the error was not more than ± 3 percent. Measurements were made only near room temperature.

This method has several disadvantages when measuring samples over a wide temperature range. A great number of pairs of liquids are needed and samples that are calibrated over this range are also needed. If these calibrated samples are not available then the following errors may result: a) the boiling points could differ slightly from the assumed values owing to impurities in the liquids, and b) the ends of the samples could not attain the boiling point temperatures due to contact resistances to heat transfer. Also when measurements were made at temperatures different from room temperature, it would be necessary to surround both liquid vessels and the sample by heat shields held at appropriate temperatures. The heat shields are needed to minimize heat transfer between the samples and the surroundings.

Line Source Method

Underwood and McTaggart (15) describe this transient method of measuring the conductivity of plastics. If heat is supplied to an infinite solid at a constant rate along a line, the temperature rise with time of a point near the line is a function of the rate of energy input and the properties of the solid. It can be represented by:

$$t(\tau) = q/2\pi k \int_{rN}^{\infty} \frac{e^{-\beta^2}}{\beta}\, d\beta = \frac{q}{2\pi k}\left[I(rN)\right] \tag{12}$$

where

$$N = 1/2\sqrt{\alpha\tau} \tag{13}$$

$$I(rN) = c - \ln(rN) + \frac{(rN)^2}{2} - \frac{(rN)^4}{8} + \ldots \tag{14}$$

If the temperature at two different times τ_1 and τ_2 is measured, a very simple expression for the temperature rise in that time interval is obtained by subtracting equation (12) for the temperature at τ_1 from equation (12) for the temperature at τ_2. Thus

$$t(\tau_2)-t(\tau_1) = q/4\pi k \ \ln(\tau_2/\tau_1) \qquad (15)$$

This equation is valid provided, that r is chosen small enough and τ large enough for the third and subsequent terms of the series (14) to be neglected. The actual value of r does not appear in the final equation, and the thermal diffusivity α also disappears. The remaining independent variables are temperature, time, and rate of heat input. These three quantities are easy to measure.

The experimental equipment consists simply of a fine (30 gauge) wire of known resistance wrapped several turns with a thermocouple and then embedded in the sample. An ordinary 6 volt storage battery supplies electric current to the wire, and an ammeter is used to measure the current flow. A potentiometer is used for the temperature read out, and a stopwatch is used for the measurement of time. Several corrections are required because a fine resistance wire only approximates a line source of heat and there may be a resistance (such as an air film) between the source and the sample. Since mathematically the model is to be an infinite solid, the duration of the test must be less than that required for the heat flow to reach a solid boundary.

This method has several advantages, some of which are: 1) the equipment needed is very inexpensive, 2) the test can be performed in a matter of minutes, and 3) the thermal conductivity is determined directly. Unfortunately, the method cannot be adapted for measurements on beef, since the mathematical model requires axisymmetrical heat flow. The heat flow would not be axisymmetrical in nonisotropic substances such as beef.

Heat Flow Meter Method

The method of measuring the thermal conductivity of beef selected for this research is a steady state method, very similar to one described by Pelanne and Bradley (16). As in the guarded hot plate method, the heat flow is one-dimensional and is described by the Fourier equation. The conductivity is calculated from the temperature difference across the sample, thickness of the sample, and the heat flow. In contrast to measuring the energy input to a heater, the heat flow is measured by allowing it to pass through a sample of known conductivity as well as the unknown sample. The known sample is a heat meter, and along with the rest of the apparatus, will be described more fully in the next chapter.

CHAPTER III

EXPERIMENTAL INVESTIGATION

Instrumentation and Equipment

Heat Flow

The meat sample and heat meter were placed between a hot and cold plate as shown in Figure 1. The temperatures of these plates were controlled separately by passing ethylene glycol solutions through them. The entire assembly was held together by one inch bolts passing through the four corners of the extreme top and bottom plates (cover plates).

The construction of both plates was identical and is shown in Figure 2. The heat transfer plate, or the plate adjacent to the sample, was a copper plate 1/4 by 9 by 9 inches. The coil structure was made separately and then soldered to the top of the copper plate with lead solder. The spaces between the coil pipes were completely filled with solder to insure good contact. The coil was made of 3/4 inch copper pipe, whose pieces were cut at 45° on the end and silver-soldered together. This method of joining the pieces was preferred over the use of fittings, in order to conserve space. The reason for choosing the flow pattern shown was to try to obtain a uniform temperature distribution on the plate. The steel cover plate was held in place by 1/4 inch brass bolts which were soldered into the top or back of the surface plate. The sides were closed by attaching 1/8 inch flexible rubber with strong glue to the edges of the copper and cover plates. The space between the top of the coils and cover plate was filled with fiberglas

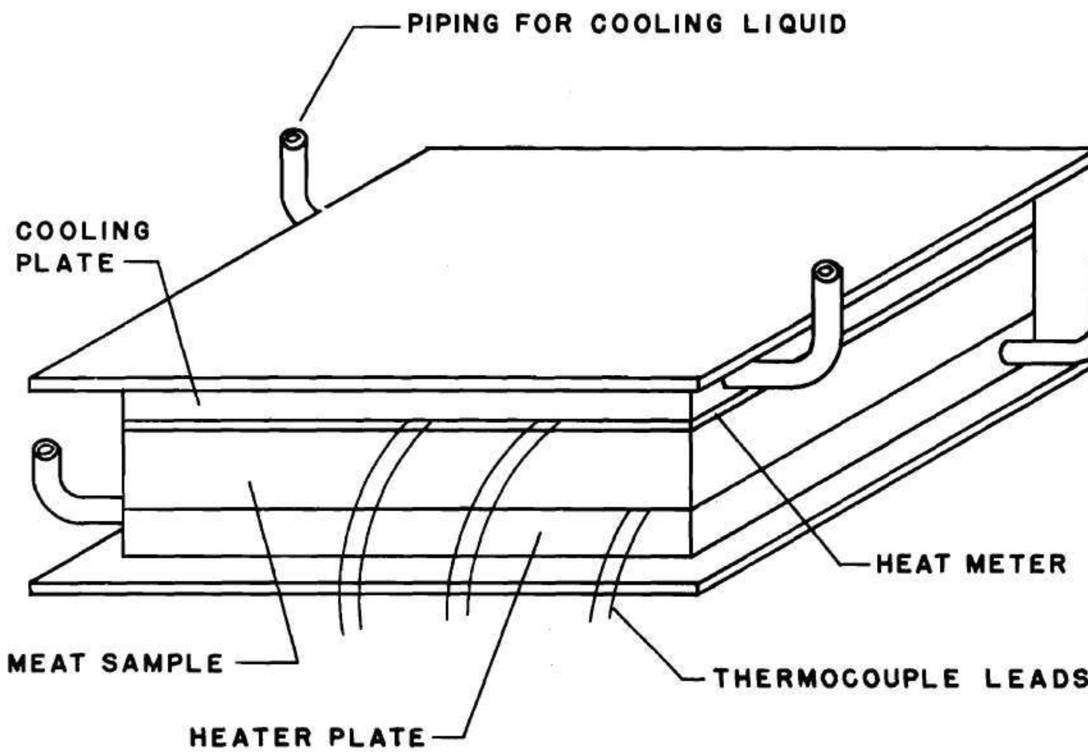

Figure 1. Hot and Cold Plate Assembly.

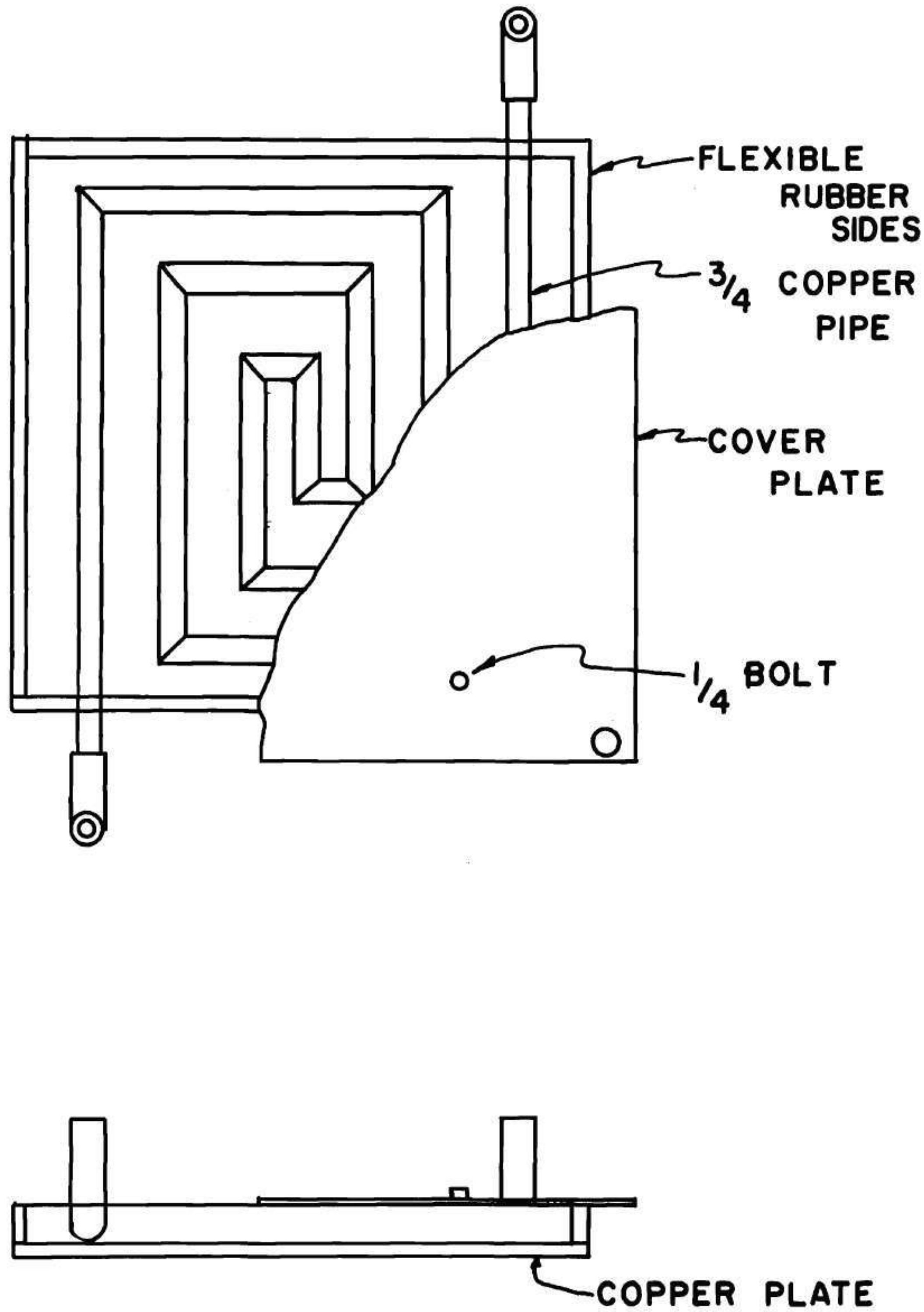

Figure 2. Cooling and Heating Plate.

insulation. The surface of the copper plate was smoothed with emery paper and painted with a light coat of dull black paint.

Plate Temperature Control

The temperatures of the ethylene glycol solutions passing through the plates were controlled by a constant temperature bath system (Figure 3). The two anti-freeze solution containers held 10 gallons and were surrounded by 2 1/2 inches of blanket insulation. The hot plate bath contained a variable output 2500 watt immersion heater, and the cold plate bath contained at 850 watt variable output immersion heater. These heaters were set for a constant power output depending on the tank temperatures required. The stirring motors kept the solutions completely mixed. The pumps used for circulating the anti-freeze mixtures were Oberdorfer* 1/12 horsepower model number 5180 centrifugal pumps, which were driven by 1/3 horsepower electric motors. They were placed in a position to pull the constant temperature liquids from the tanks through the plates rather than pumping the liquids to the plates. This allowed the uniform temperature fluids to pass directly to the plates without the addition of heat from the pumps.

The thermostats operated the solenoid valves to deflect the return flow through cooling coils in the heat exchanger when the tank temperatures were higher than the thermostat settings. The thermostats were Fenwall** immersion thermoswitches number 17800-0. The solenoid valves were ASCO***

---

*Oberdorfer Foundries, Incorporated, Syracuse, New York.

**Fenwall, Incorporated, Ashland, Massachusetts.

***Automatic Switch Company, Florham Park, New Jersey.

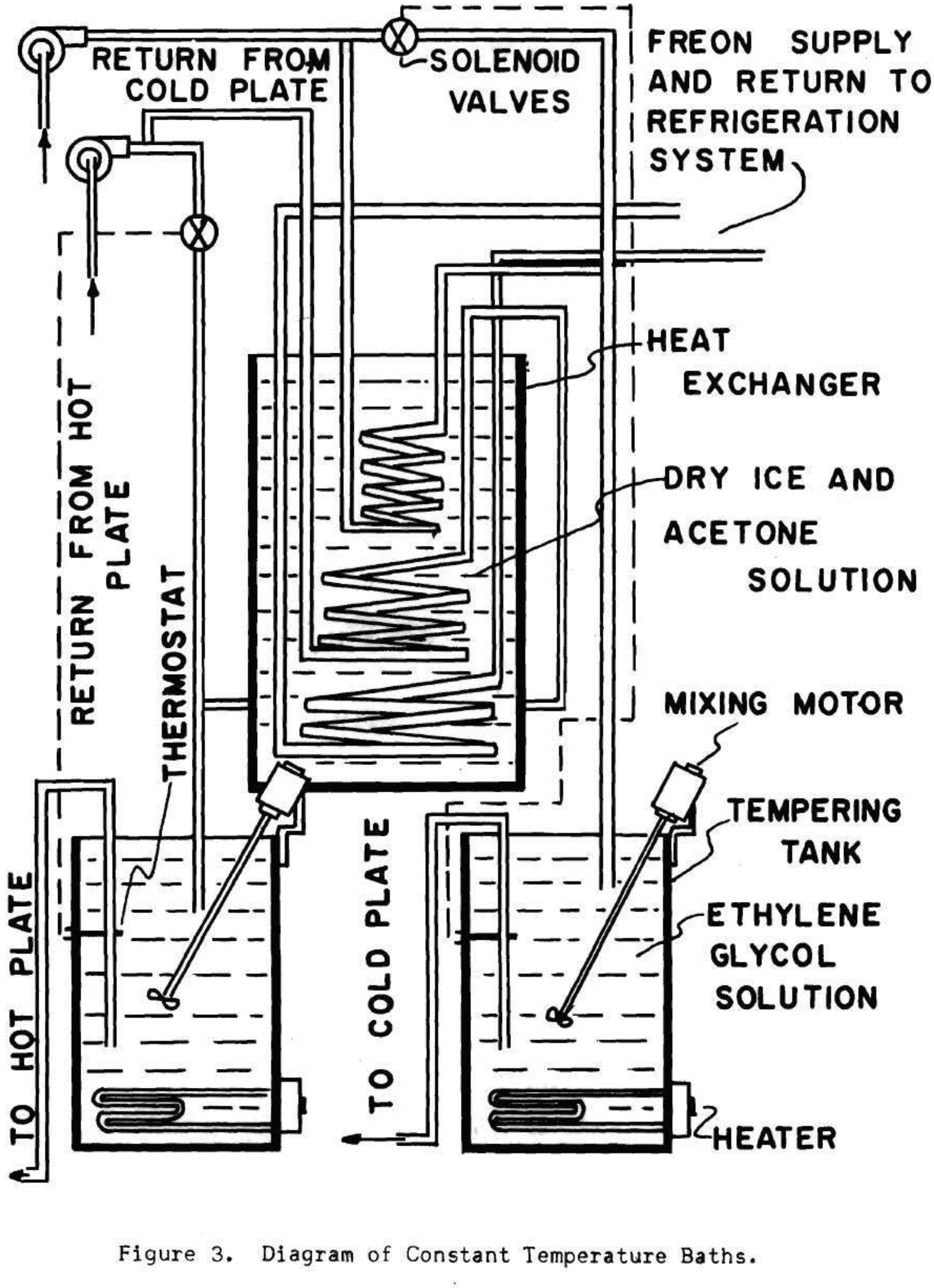

Figure 3. Diagram of Constant Temperature Baths.

valves number 8030A1. The cooling tub was a 20 gallon container of acetone and dry ice which was surrounded by 2 1/2 inches of blanket fiberglas insulation. The dry ice was used only to supplement the refrigeration unit, which was a Copeland* model number CSAL-0100-CAB-001 which used refrigerant 12.

Heat Meter

The heat meter was a specially designed model number T200-3 manufactured by the Beckman and Whitely Company.** The design is shown in Figure 4.

The multi-junction thermopile elements are arranged in a thin bakelite plate. The thermopile consists of a series of silver-constantan thermocouples which are positioned so that one set of junctions (cold junctions) is in a plane adjacent and parallel to one face of the plate, and the other set of junctions (hot junctions) is in a plane adjacent and parallel to the other face of the plate. Heat flow through the plate will generate an electromotive force due to the difference in temperature of the hot and cold junctions of the thermopile. The measuring junctions are centrally located in the plate and cover an area of 4 inches by 4 inches. The plate dimensions are 9 inches by 9 inches by 3/64 inch. Therefore, if the flow is not truly one-dimensional near the sides due to edge effects, it will have no significant influence on the results.

The meter was calibrated by comparison with known heat flows, so that with the aid of a correction curve (Figure 5) an output reading could be converted directly into heat flow rate. At 80°F, one millivolt output

---

*Copeland Refrigeration Corporation, Sidney, Ohio.

**Beckman and Whitely, Incorporated, San Carlos, California.

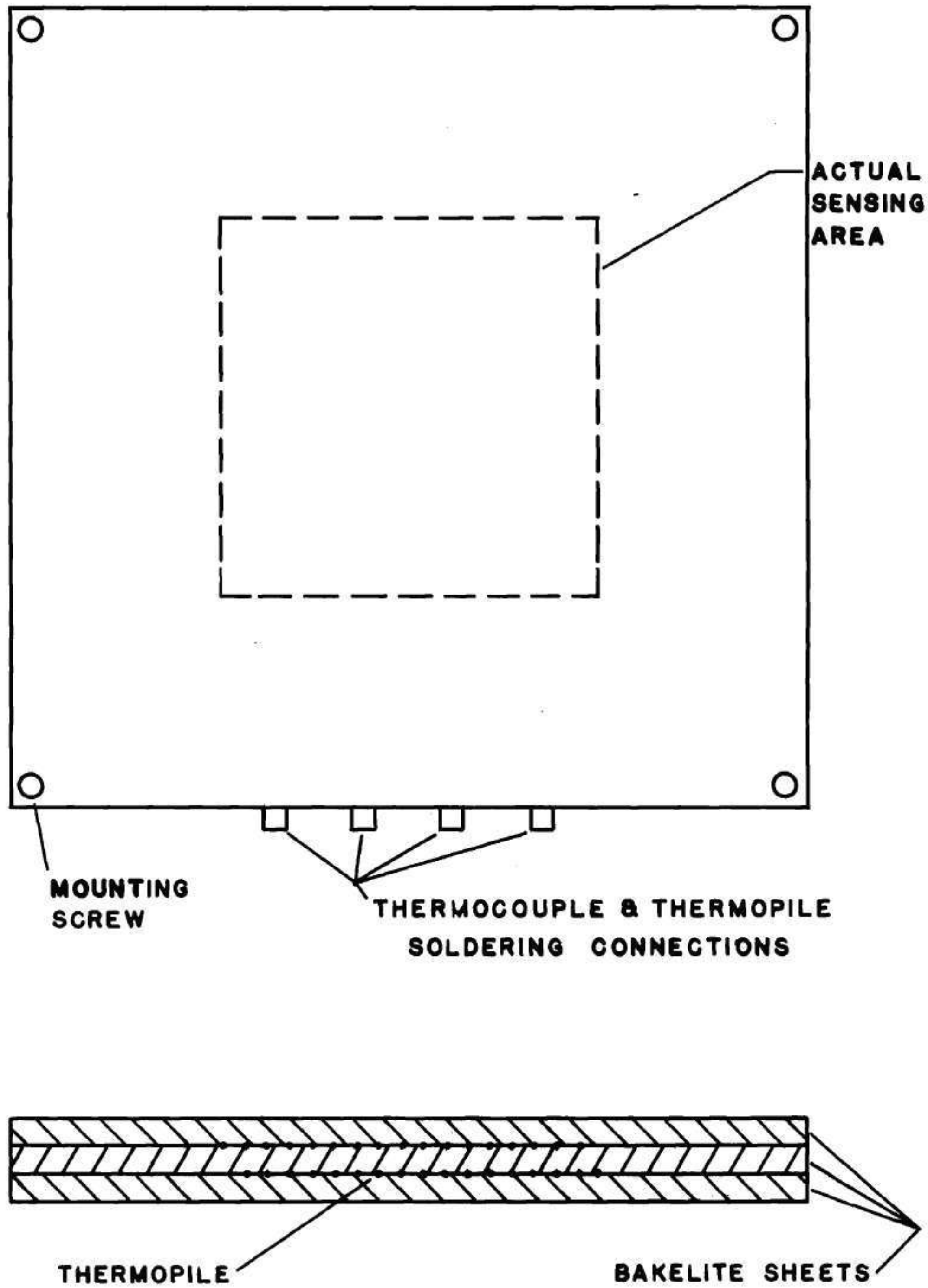

Figure 4. Heat Flow Transducer.

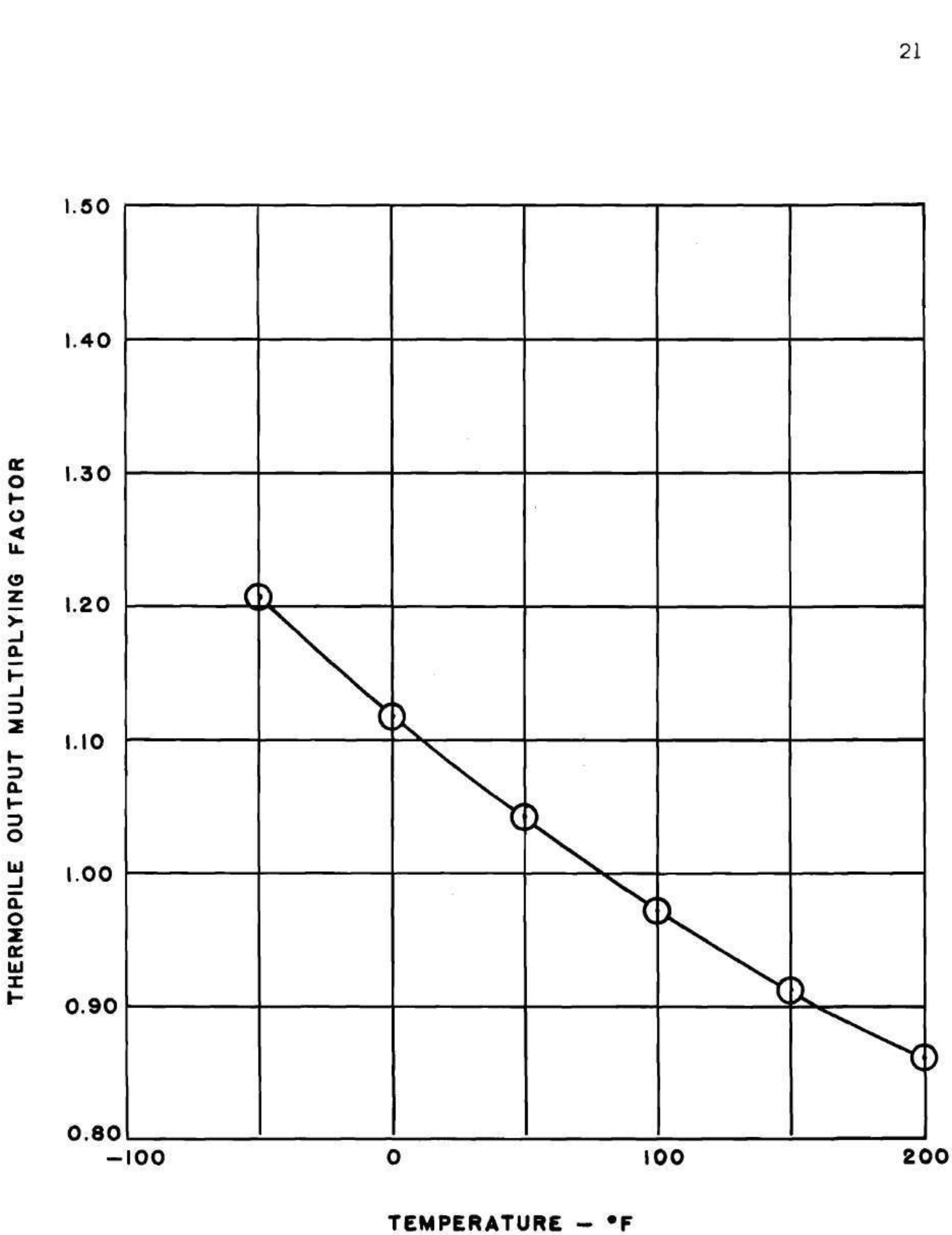

Figure 5. Heat Meter Calibration Curve.

was equivalent to 5.76 Btu/hr ft °F. Figure 5 allowed for a correction for the temperature-coupled variations in the thermopile output. This curve was supplied with the heat meter. The output of the thermopile was read on a model number 8686 Leeds and Northrup* precision portable potentiometer.

Temperature Measurement

The arrangement for measuring the temperature drop across the sample is shown in Figure 6. The thermocouple junctions were all copper constantan, made from Leeds and Northrup 30 gauge thermocouple wire, and attached by a heat welding process with no other metal involved in the junction of the two wires. The ice baths were dewar vacuum flasks containing a mixture of crushed ice and water. The accuracy of the entire system was checked by calibrating against a set of secondary standard mercury-in-glass thermometers. The junctions 1, 2, 3, and 4 were attached to the surface of the copper plate in contact with one surface of the sample and the junctions 1', 2', 3', and 4' were attached to the other side of the sample. The output was magnified by the number of couples in series and thus permitted the detection of very small temperature differences. One observation gave the arithimetic mean of the temperature difference sensed by the two groups of four measuring junctions when the total emf was divided by four. A separate thermocouple was attached to one surface in order to indicate the temperature level. The potentiometer used was a Leeds and Northrup model number 8686 precision portable potentiometer.

---

*Leeds and Northrup Company, Philadelphia 44, Pennsylvania.

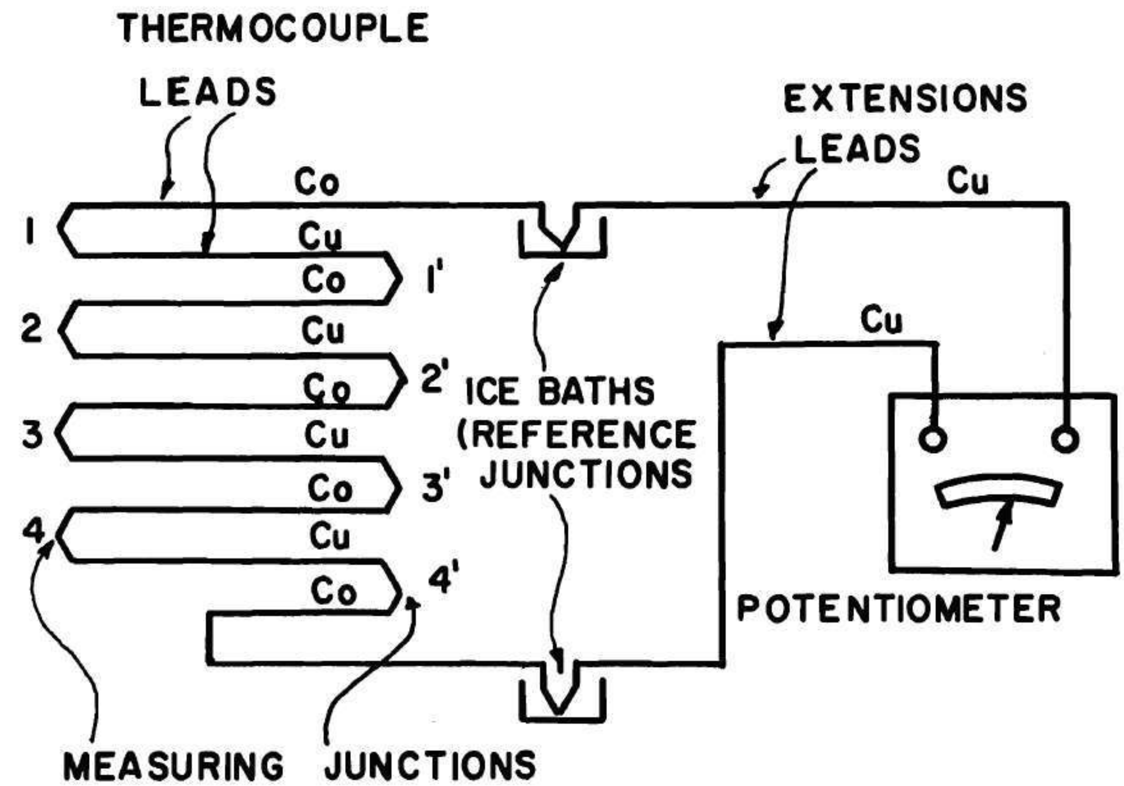

Figure 6. Differential Temperature Measurement.

Experimental Procedure

Sample Preparation

The samples of beef used were taken from the inside round and of canner and cutter grade. This type of beef was chosen because it was extremely lean and could be bought in large pieces, enabling good sized samples to be cut from them. The pieces were placed in plastic bags and frozen in a home freezer for approximately two weeks. They were then removed and cut on a band saw in order to obtain the samples in slab form. For the test where the heat flowed perpendicular to the grain of the meat, it was possible to cut one slab approximately 9 inches square and 1 1/2 inches thick. For the test parallel to the grain, several smaller pieces had to be cut and placed together in order to make the 9 inch sample. The samples were weighed and then refrozen for approximately a day before the beginning of the tests.

Conductivity Measurement

The experimental procedure used for measuring the conductivity and determining the moisture content of the samples is as follows:

1. The refrigeration unit was started.

2. The thermopile for determining the temperature drop across the sample and the thermocouple for sensing the temperature level were checked for correct readings by comparison with a set of standard mercury-in-glass thermometers. The thermopile and the thermocouple were attached to the plates of the apparatus.

3. The sample was removed from the freezer and weighed.

4. The surface of the meat was wetted and then placed in the hot and cold plate assembly. The wetting insured good contact at both

surfaces of the sample.

5. The corner bolts were adjusted until the sample was held firmly between the plates and there was the same distance across the sample on all four sides. A set of inside calipers used in conjunction with another set of outside vernier calipers was used to measure the distance.

6. The pumps circulating the anti-freeze solution through the plates were started.

7. The thermostats were set at approximately the settings for the first data point.

8. Dry ice was added to the acetone in the heat exchanger, and then again whenever needed to maintain the heat exchanger at a temperature well below the cold plate temperature.

9. Three inches of rigid fiberglas insulation were placed against the four sides of the hot and cold plate assembly. The entire assembly was wrapped with 2 1/2 inches of blanket insulation and then enclosed in polyethylene. Silica gel was placed in the bottom of the enclosure to keep the insulation dry throughout the tests.

10. Since the thermostats were not marked directly in terms of temperature, they had to be adjusted several times to obtain the correct average temperature level. A temperature drop across the sample of at least 30°F was maintained if possible at all data points. This was not feasible at points near the thawing region.

11. Readings from the heat meter, thermopile, and thermocouple were taken every half an hour until steady state was reached. Values were then read every 10 minutes for two to three hours, and all the

readings were averaged for the calculation of conductivity.

12. All the data points in the frozen region were taken first. They were taken in a random order to make certain that there was no error as a result of approaching all points from either a lower or upper temperature.

13. The plate temperatures were increased and the sample was allowed to thaw completely before the data were taken in the unfrozen region (the points again being selected in a random order).

14. After all data had been taken, the sample was removed, weighed again, and refrozen.

15. The sample was then placed in a freeze-drying chamber and dried until no change of weight could be detected for a period of several hours. It was removed and weighed.

The above procedure was identical for the sample measured perpendicular to the grain and the one measured parallel to the grain. A third sample was cut from a fresh piece of beef so that the heat would flow perpendicular to the grain, and one data point was taken in the unfrozen region, to determine if there was any change in the data when compared with the sample that had been frozen before taking data in the unfrozen region.

Discussion of Experimental Accuracy

The overall accuracy of the experimental set-up was investigated by measuring the thermal conductivity of a slab of paraffin wax and of a slab of white oak perpendicular to the grain, and comparing the results with handbook values. The value for paraffin was 3.75 percent lower than the handbook value and that for the white oak was 8.4 percent high. These values were considered good. In the case of the wood sample, the moisture had not been removed and this no doubt caused the high result.

CHAPTER IV

PRESENTATION AND DISCUSSION OF RESULTS

The results obtained from the experimental investigation are shown in Figures 7 through 10. The conductivity values are plotted in Figures 7 and 8 as a function of temperature and compared with results obtained by other investigators. In Figure 9 the values are plotted as a function of temperature and compared with the values obtained from a mathematical model proposed by Miller and Sunderland (20). In summary, all available data is plotted and compared in Figure 10.

The fat content of the samples used in the present work was calculated by using relationships presented by Callow (19). He suggested that the following equations could be used in relating fat content to water and to dry non-fatty residue:

$$W = 78.4 - .808\ F$$

$$R = 21.6 - .192\ F$$

The dry residue is 90 percent protein and the equations are valid for beef. W, F, and R are the percent of the total weight which is water, fat, and residue respectively. These formulas were determined from data taken from five different breeds ranging in age from one week to ten years. Some of the animals were well fed, and some were emaciated.

In Figure 7 data are shown for conductivity of samples of beef

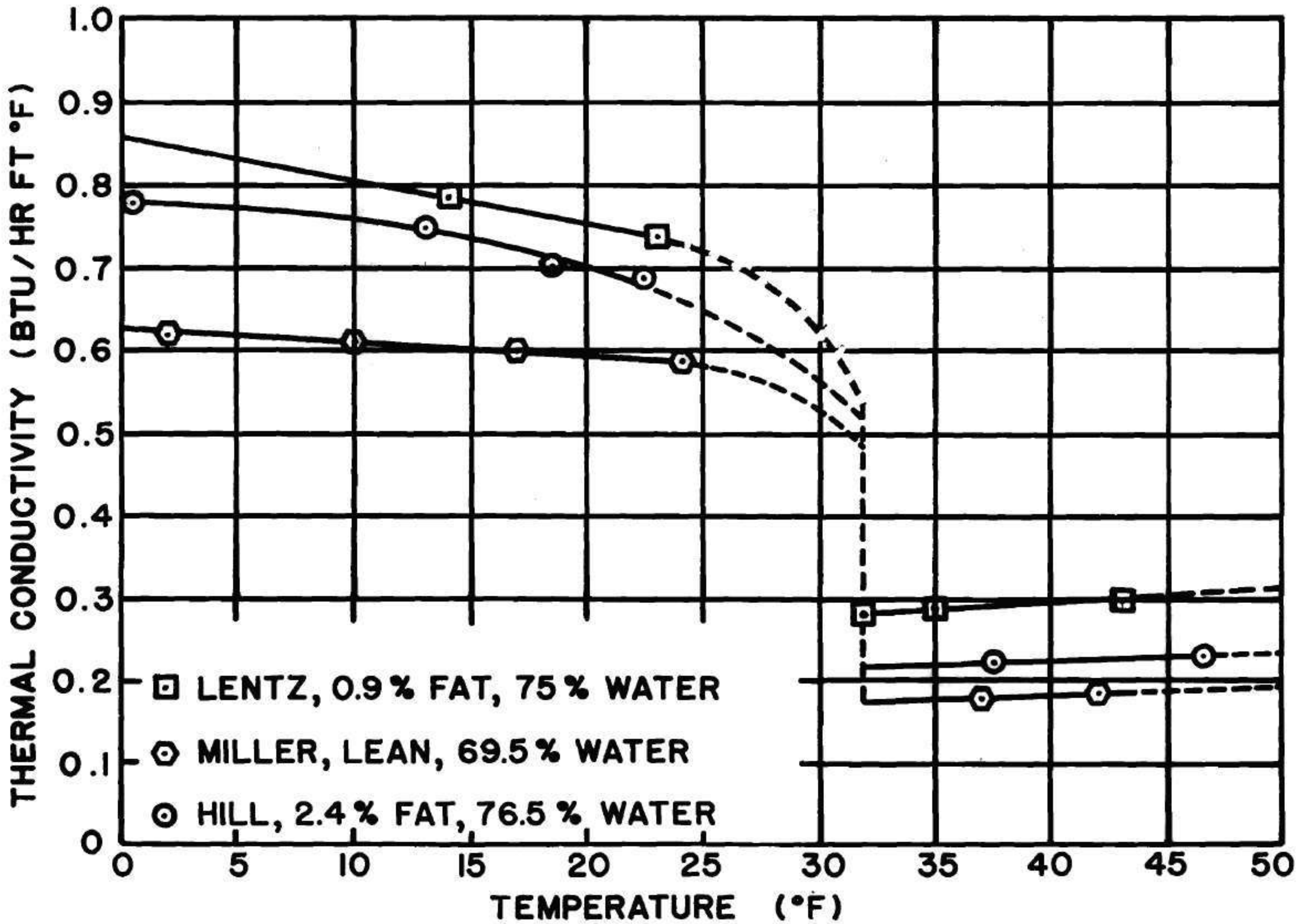

Figure 7. Thermal Conductivity versus Temperature for Lean Beef, Parallel to the Grain.

which were cut so that the heat flow was parallel to the grain of the beef. Above freezing, the conductivity increases as the temperature increases. Below freezing, the conductivity varies inversely with temperature. This variation of thermal conductivity with temperature follows the same trend as the thermal conductivity of ice and water (see Appendix B). Between 22 and 32°F the experimental data are not conclusive, since the percent of meat frozen varies with temperature in this range. It is estimated by Miller (7) that the percent of moisture frozen, and hence also the thermal conductivity, varies abruptly with temperature at 31°F. The data above 32°F, in all three cases, apply to samples that were previously frozen. It was expected that the conductivity would be higher for samples containing a higher moisture content. There is no obvious explanation for the observation that the data obtained by this investigator were not higher than that obtained by Lentz (6).

In Figure 8 data are plotted for conductivity of samples of beef which were cut so the heat flow was perpendicular to the grain of the beef. As in Figure 7, above freezing the conductivity increases as the temperature increases, while below freezing the conductivity varies inversely with temperature. As can be seen, the conductivity of beef will increase as the moisture content increases. Miller states that since freezing may alter the characteristics of the structure of the beef tissue, values of conductivity measured above the freezing point for samples previously frozen and for samples previously not frozen, may not agree. The data of this investigation, for beef measured perpendicular to the grain above the freezing point, consist of one point measured

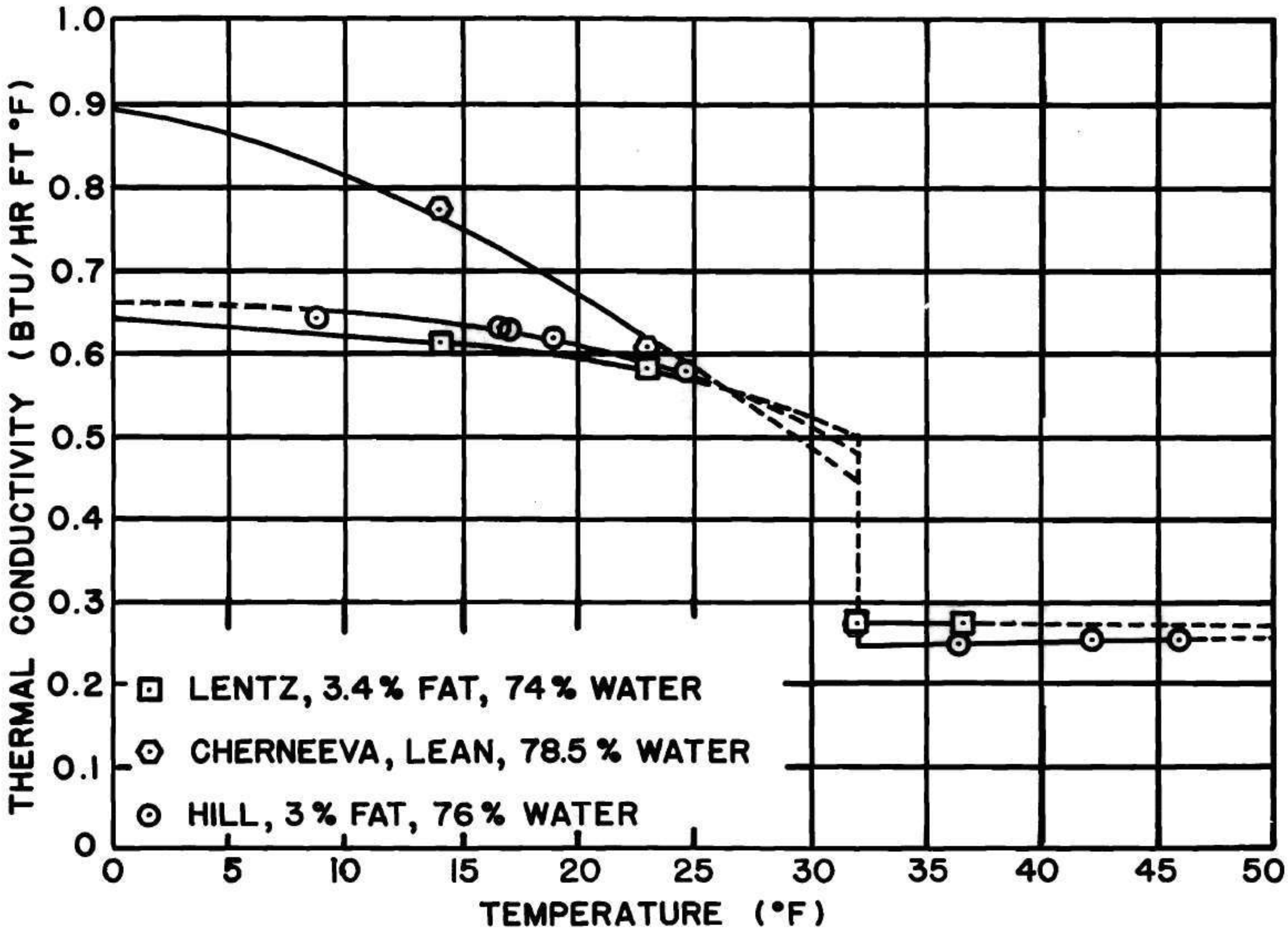

Figure 8. Thermal Conductivity versus Temperature for Lean Beef, Perpendicular to the Grain.

prior to freezing and three points measured after the sample had been frozen. The data, as shown on the graph, correlate very well. While no significant conclusions can be drawn from one measurement, it might aid in leading to the conclusion that the conductivity may not depend on whether the sample is previously frozen.

Miller and Sunderland (20) present a mathematical model useful for predicting the thermal conductivity of beef in a direction parallel to the fiber for beef with a moisture content of 60 percent and higher. This model is presented in Appendix B. In order to use the model for the calculation of conductivity, only the moisture content is needed. In Figure 9 data of this investigation as well as data by Miller are plotted as a function of temperature and compared with the respective values calculated by using the model. Excellent agreement is seen in the frozen region from 0 to 22°F. In the region above freezing the model predicts values slightly higher than were obtained experimentally. For a moisture content of 75 percent, the model predicts values of thermal conductivity 11 percent lower than the measurements made by Lentz in the temperature range 0 to 22°F. Again the model seems to work extremely well in the frozen region, and this will be the main area of its application. It will aid in predicting conductivity values of samples to be freeze-dried.

Harper and El Sahrigi (8) present a model for the calculation of the thermal conductivity of a porous solid. The general equation that is presented contains four constants that have to be evaluated using four specified conditions. They adapt the equation to a gas-filled solid so that it can be used to calculate the conductivity of freeze-dried

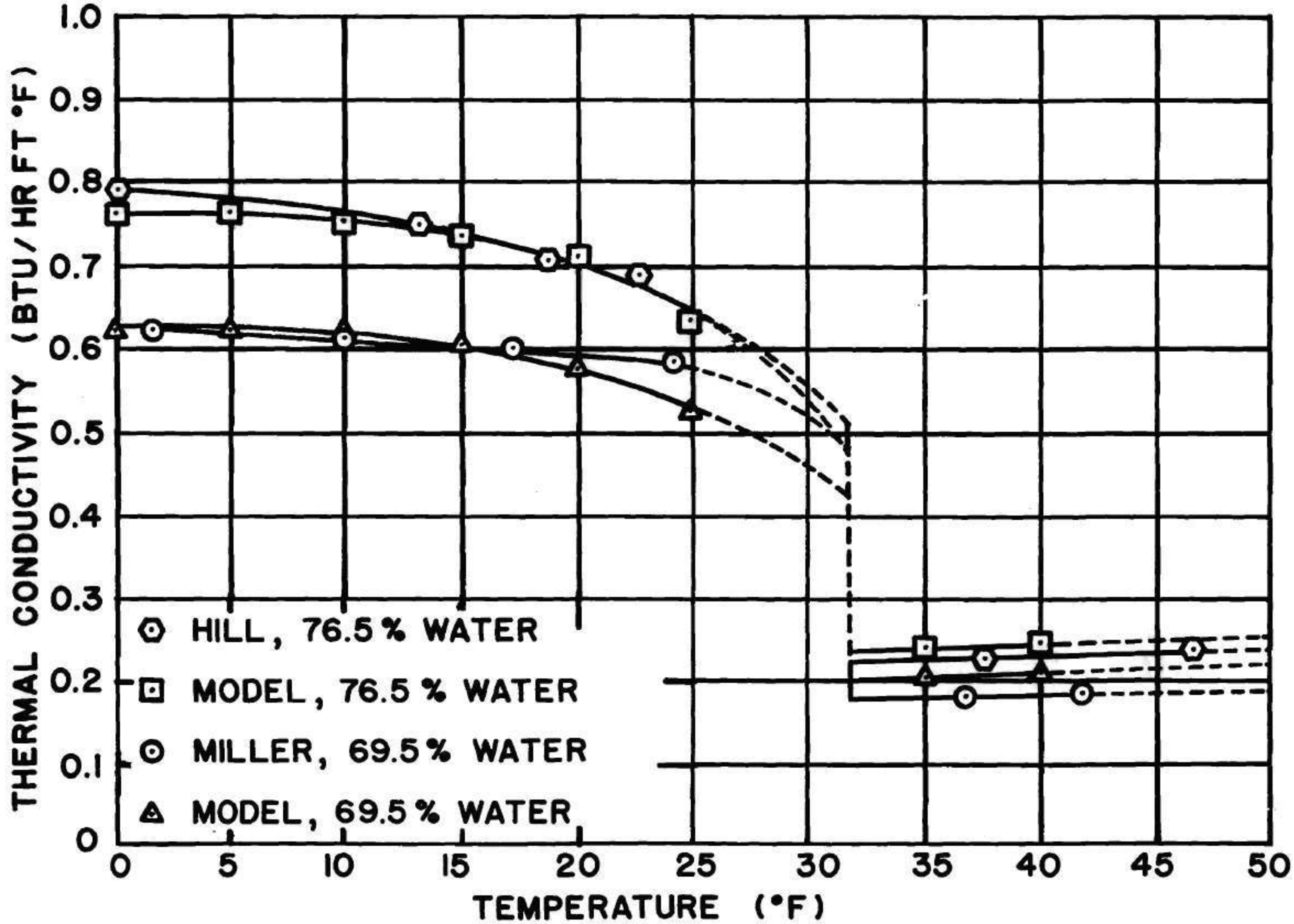

Figure 9. Thermal Conductivity versus Temperature for Lean Beef, Parallel to the Grain.

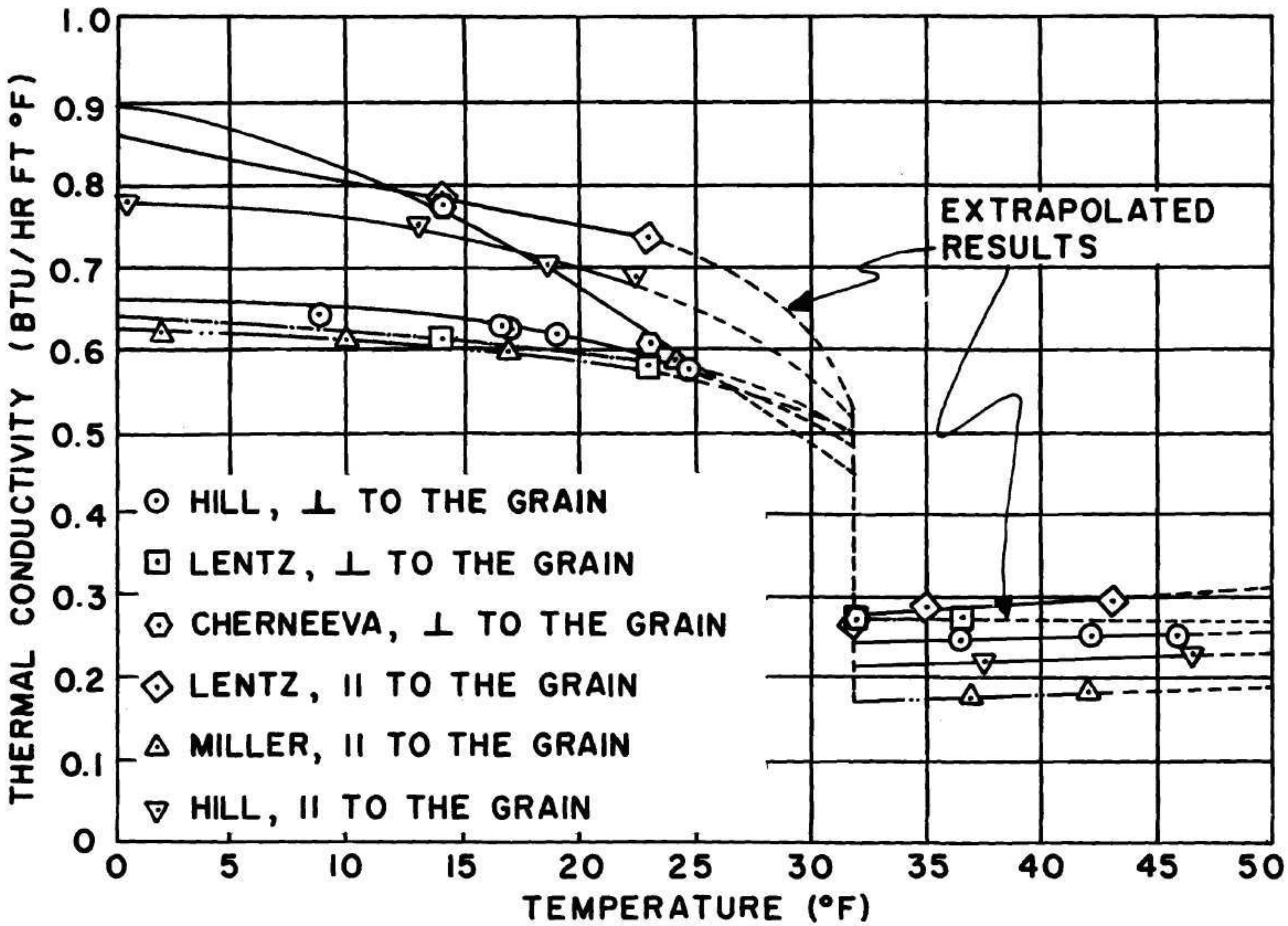

Figure 10. Thermal Conductivity versus Temperature for Lean Beef.

beef. The resulting equation does not seem to be applicable to fresh or frozen beef because of the conditions which they use to evaluate the constants. No extensive work has been done to determine whether the general model could be adapted for the use with fresh or frozen beef.

In Figure 10, the data of Figures 7 and 8 are plotted together as a summary of all the available data for the conductivity of nondehydrated beef. All of the curves show the same dependence of conductivity on temperature. As can be seen by comparing the two sets of data of this investigation, in the frozen region the conductivity of the sample measured parallel to the grain is approximately 16 percent higher than the sample measured perpendicular to the grain. This is in good agreement with Lentz, who states that the difference should be 15 to 30 percent. However, in the region above freezing the conductivity of the sample measured parallel to the grain dropped below that of the other sample. This would not be expected normally.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

An experimental investigation has been made to determine the thermal conductivity of nondehydrated beef.

The conclusions drawn from this investigation are:

1. For frozen beef, the thermal conductivity varies inversely with temperature, whether the heat flow is parallel or perpendicular to the grain of the fiber.

2. For fresh beef, the thermal conductivity increases with temperature, whether the heat flow is parallel or perpendicular to the grain of the fiber.

3. For frozen beef, the thermal conductivity will be higher in a direction parallel to the fiber of the meat than in a direction perpendicular to the fiber.

4. The thermal conductivity of beef in a given direction will be higher for samples having higher moisture contents.

5. Between 22 and 32°F, the experimental data is not conclusive, since the percent of meat frozen varies with temperature in this range.

6. The mathematical model presented by Miller and Sunderland (20) is very useful for predicting the thermal conductivity of beef from 0 to 22°F in a direction parallel to the fiber and for beef with a moisture content of 60 percent or higher.

7. For one measurement, the thermal conductivity of fresh beef

did not depend on whether it had been previously frozen.

The following items are recommended as a logical extension of the work which has been presented in this thesis:

1. Additional data should be taken on samples in the unfrozen region both before and after freezing to verify that the conductivity does not depend upon whether the beef was previously frozen.

2. Data should be taken on samples of beef in the temperature range 50 to 150°F.

3. Additional data should be taken on samples at various moisture contents parallel to the grain, to test the validity of the meat model at these moisture contents.

4. An extensive study should be made to determine the dependence of thermal conductivity on the grazing, feeding, and general condition of the cattle.

5. A study should also be made to determine the dependence of thermal conductivity on fat content.

APPENDIX A

THERMAL CONDUCTIVITY DATA

Table 1. Thermal Conductivity of Nondehydrated Beef by Previous Investigators

Reference	Material	Percent Moisture	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity $\frac{Btu}{Hr\ ^{o}F\ Ft}$
1	Beef			-200	0.895
2	Muscle				0.114
	Fat				0.118
4	Beef, lean	78.5	Perpendicular	32	0.277
				23	0.612
				14	0.779
				-4	0.907
	Beef, fat	74.5	Perpendicular	32	0.277
				23	0.537
				14	0.692
				-4	0.827
	Beef, fat	7		32	0.118
				23	0.122
				14	0.131
				-4	0.141
6	Beef, lean, Flank, (3.4% fat)	74	Perpendicular	36.5	0.279
				32	0.2785
				23	0.588
				14	0.616
				-4	0.675
	Beef, lean, Sirloin, (0.9% fat)	75	Parallel	43	0.30
				35	0.290
				32	0.284
				23	0.742
				14	0.792
				-4	0.904
	Beef, Udder, (89% fat)	9		23	0.166
				14	0.148
7	Beef, lean, eye of Loin, U.S. Good Grade	69.5	Parallel	42	0.185
				37	0.18
				24	0.59
				17	0.60
				10	0.61
				2	0.62

Table 2. Thermal Conductivity of Dehydrated Beef by Previous Investigators

Reference	Material	Pressure mm Hg	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity $\frac{Btu}{Hr\ Ft\ °F}$
3	Beef				0.02
5	Beef, Muscle	760	Parallel	58	0.0375
	Beef, Muscle	0.01	Parallel	58	0.0216
8	Beef, Muscle (pores filled with N_2)	0.005	Parallel	95	0.0218
		0.007		95	0.0218
		0.013		95	0.0218
		0.023		95	0.0218
		0.051		95	0.0222
		0.104		95	0.023
		0.220		95	0.0242
		0.410		95	0.0258
		0.840		95	0.0278
		1.670		95	0.0297
		3.100		95	0.0316
		5.3		95	0.0332
		11.0		95	0.0352
		20.0		95	0.0370
		57.0		95	0.03775
		112.0		95	0.0378
		250.0		95	0.0378
		760.0		95	0.0378
9	Beef, Muscle	0.2	Parallel	35	0.0305
		0.5		43	0.0358
		0.7		46	0.0384
		1.0		53	0.0416
		2.0		57	0.0421
		3.0		62	0.0429

Table 3. Thermal Conductivity Data of Nondehydrated Beef

Material	Percent Moisture	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity $\frac{Btu}{Hr\ Ft\ ^{o}F}$
Beef,	76	Perpendicular	8.6	0.647
lean,			17.0	0.632
Inside			16.5	0.635
Round,			18.9	0.623
Canner and			24.6	0.583
Cutter			36.3	0.252
Grade,			42.1	0.255
(3% fat)			45.8	0.256
			46.3	0.257
Beef,	76.5	Parallel	0.3	0.796
lean,			13.0	0.750
Inside			18.4	0.701
Round,			22.3	0.690
Canner and			37.5	0.230
Cutter			46.5	0.232
Grade,				
(2.35% fat)				

APPENDIX B

STRUCTURAL MODEL FOR MEAT

In order to extrapolate the experimental results of the thermal conductivity of beef muscle for different moisture contents, Miller and Sunderland (20) proposed that the model in Figure 11 could be used. The model is made up of fibers arranged parallel and normal to the heat flow path; the remaining space is assumed to be filled with water or ice. The model has three parallel paths for heat transfer. The first path is composed only of fibers; the second path is water (or ice); the third path is a series arrangement of water (or ice) and fibers. It is assumed that no energy crosses the boundaries between the paths and that heat is transferred only by thermal conduction. The equivalent electrical circuit of the three paths is shown in Figure 12.

Consider an area equal to P^2 which lies in a plane perpendicular to the direction of heat transfer . If the total sample thickness is Δx, the thickness of each layer of fibers (P) equals $\frac{\Delta x}{n}$, where n is the number of fiber layers. The temperature drop across each layer of the fibers is $\frac{\Delta T}{n}$, where ΔT is the temperature difference across the sample. The rate of heat conduction through the fibers (q_1) is given by:

$$q_1 = k_f \, d_1(2P - d_1) \, \frac{\Delta T}{nP}$$

where k_f is the thermal conductivity of the fibers. The rate of heat

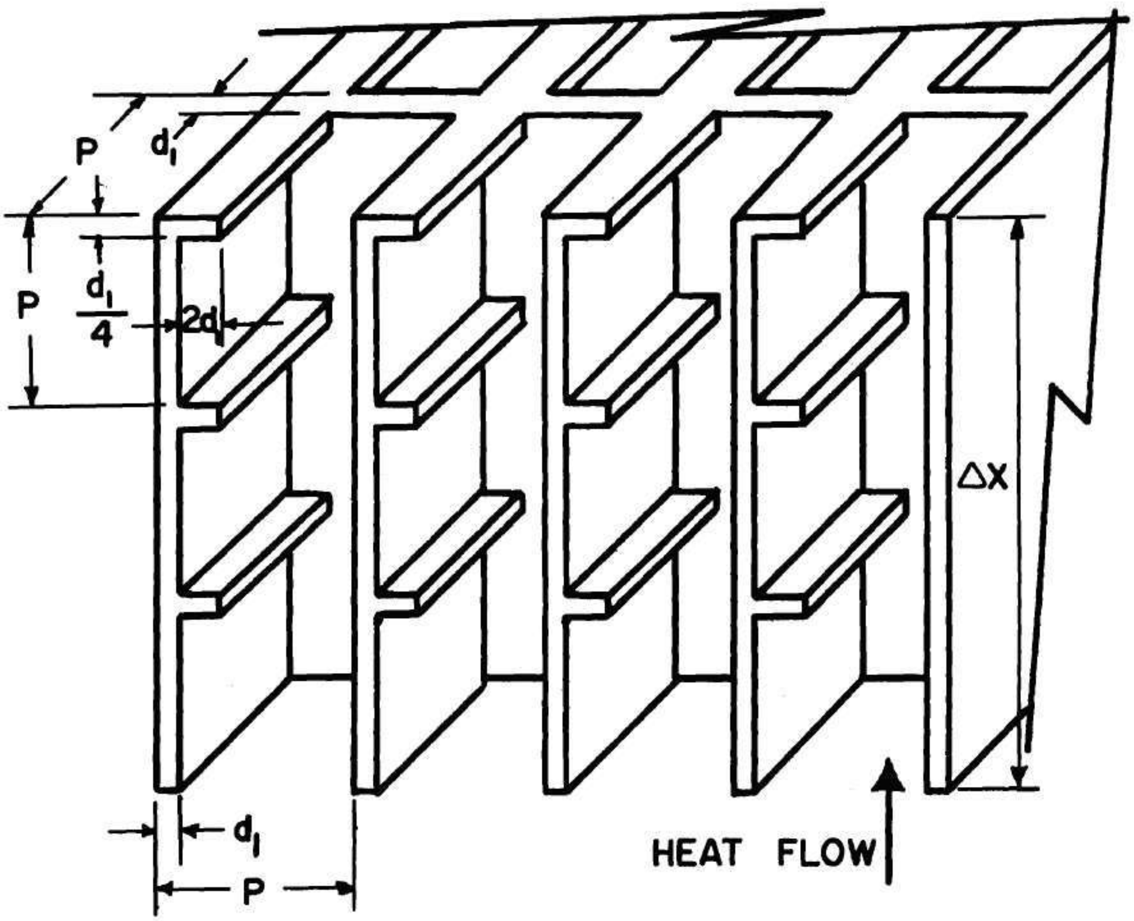

Figure 11. One Dimensional Thermal Conductivity Model for Meat.

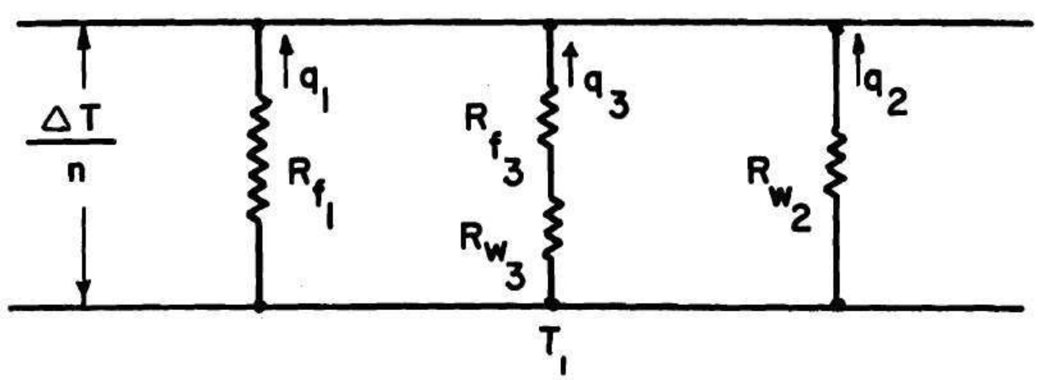

Figure 12. Analog of Heat Flow Paths Through Structural Model for Meat.

conduction through the water and/or ice (q_2) is:

$$q_2 = k_w \left[(P - d_1)^2 - 2d_1(P - d_1) \right] \frac{\Delta T}{nP}$$

or

$$q_2 = k_w \left[P^2 - 4Pd_1 + 3d_1^2 \right] \frac{\Delta T}{nP}$$

where k_w is the thermal conductivity of the water or ice. The rate of heat conduction through the water and/or ice in series with the fiber (q_3) is given by:

$$q_3 = k_{fw} \left[2d_1(P - d_1) \right] \frac{\Delta T}{nP}$$

where:

$$k_{fw} = \frac{4k_f k_w}{\frac{d_1}{P} k_w + (4 - \frac{d_1}{P})\, k_f}$$

The apparent thermal conductivity, k_a, is given by:

$$k_a = A \; \frac{q_1 + q_2 + q_3}{P^2 \frac{\Delta T}{\Delta x}}$$

Therefore it follows that:

$$k_a = k_f \left[2\frac{d_1}{P} - \left(\frac{d_1}{P}\right)^2 \right] + k_w \left[1 - 4\frac{d_1}{P} + 3\left(\frac{d_1}{P}\right)^2 \right]$$

$$+ \frac{8\, k_f k_w \left[\frac{d_1}{P} - \left(\frac{d_1}{P}\right)^2 \right]}{\frac{d_1}{P} k_w + (4 - \frac{d_1}{P})\, k_f}$$

The volume of one of the cubes (V_T) of the model is given by the sum of the fiber volume (V_f) and the water volume (V_w). That is,

$$V_T = V_f + V_w = P^3$$

From Figure 11 it can be seen that:

$$V_f = 2d_1P^2 - 1/2\, d_1{}^2P - \frac{d_1{}^3}{2}$$

Since d_1 is very small compared with P, the last term of the previous equation can be neglected. Therefore:

$$\frac{d_1}{P} = 2 - \sqrt{4 - 2V_f/V_T}$$

The negative sign must be used in front of the square root because $\frac{d_1}{P}$ is always less than one.

Since the density of fresh meat (63 lbs/ft^3) is nearly equal to the density of the fiber shown in the model (64.2 lbm/ft^3), they are assumed equal. The ratio $\frac{d_1}{P}$ can then be expressed in terms of the total weight and the fiber weight. Thus:

$$\frac{d_1}{P} = 2 - \sqrt{4 - 2\, W_f/W_T} \qquad (17)$$

Results of the calculations of the thermal conductivity based on the model for the beef with 69.5 percent and 76.5 percent water are shown in Table 4. These results are compared with experimental data in Figure 9. Harper and Chichester (5) report the thermal conductivity of meat fiber to be 0.0216 Btu/hr ft °F; in this thesis, the conductivity of meat fiber is assumed to be independent of temperature. The liquid phase is an aqueous solution which contains dissolved salts and proteins. The exact composition of this liquid phase is unknown. The conductivity values used here will be those of a 0.28 M salt solution shown in Figure 13, which have been reported by Long (21). As can be seen from the figure, the conductivity of the salt solution gradually decreases in the freezing region (22 to 32°F) as does beef. This is in contrast to the finite jump in the conductivity of distilled water at 32°F.

Table 4. Thermal Conductivity of Nondehydrated Beef Predicted by the Model

Percent Moisture	Temperature °F	Conductivity $\frac{\text{Btu}}{\text{Hr Ft }^{\circ}\text{F}}$
76.5	0	0.764
	5	0.764
	10	0.755
	15	0.737
	20	0.706
	25	0.630
	35	0.240
	40	0.249
69.5	0	0.623
	5	0.623
	10	0.615
	15	0.602
	20	0.576
	25	0.520
	35	0.207
	40	0.215

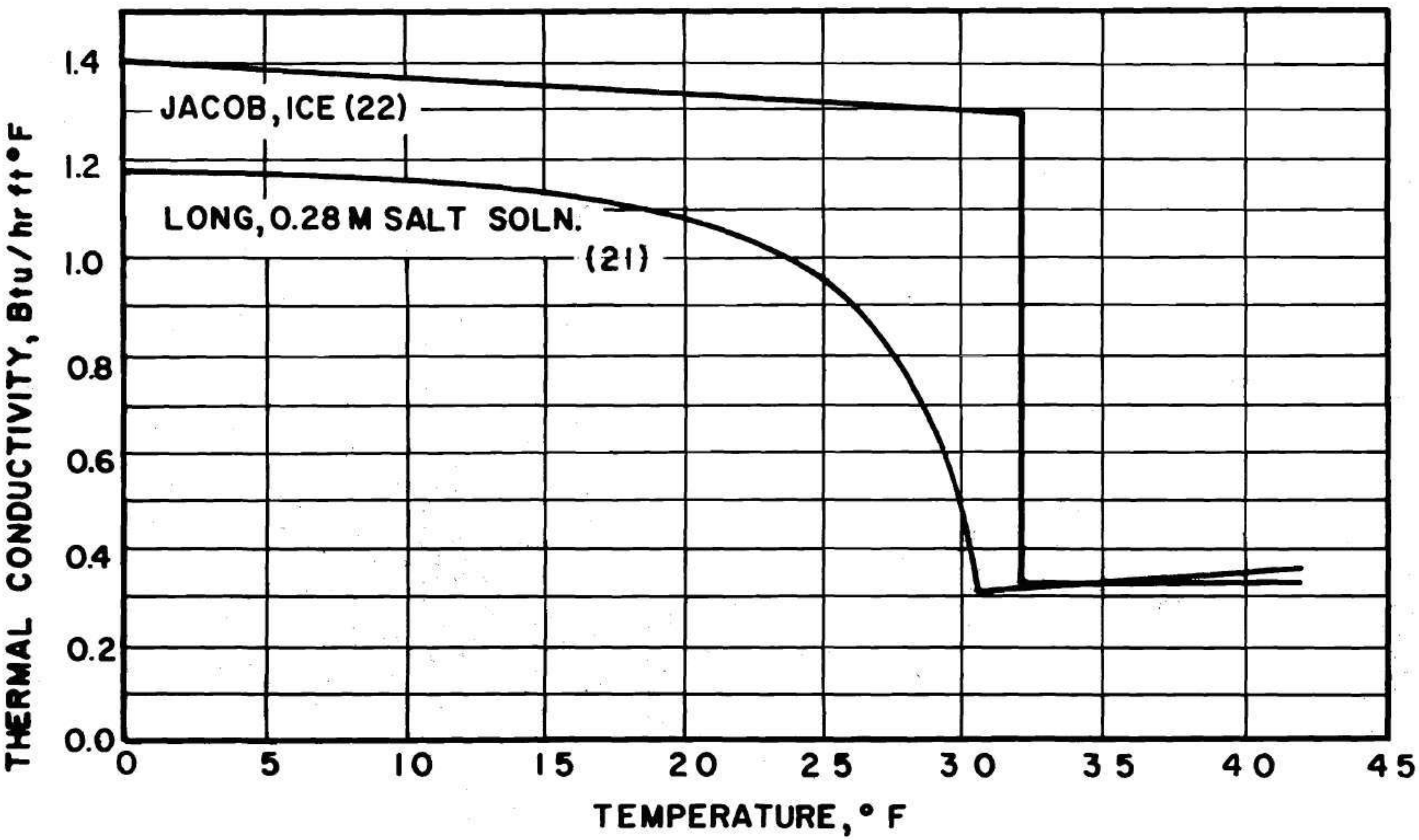

Figure 13. Thermal Conductivity versus Temperature for a Salt Solution and Ice.

LITERATURE CITED

1. J. H. Awbery and E. Griffiths, "Thermal Properties of Meat," Journal of the Society of Chemical Industry, 52, (1933), p. 326.

2. J. D. Hardy and G. F. Soderstrom, "Heat Loss from the Nude Body and Peripheral Blood Flow at 22 - 35°C," Journal of Nutrition, 16, (1938), p. 493.

3. A. L. Tappel, A. Conroy, M. R. Emerson, L. W. Regier, and G. F. Stewart, "Freeze Dried Meats, Preparations and Properties," Food Technology, 9, (1955), p. 401.

4. L. I. Cherneeva, "Study of the Thermal Properties of Foodstuff," Report of VNIKHI, Gostorgisdat, Moscow, (1956).

5. J. C. Harper and C. O. Chichester, "Micro-wave Spectra and Physical Characteristics of Fruit and Animal Products Relative to Freeze-dehydration," Final Report, University of California, Davis Quartermaster Corps Food and Container Institute Contract DA-19-129-qm-1349, (1960).

6. C. P. Lentz, "Thermal Conductivity of Meats, Fats, Gelatin Gels, and Ice," Food Technology, 15(5), (1961), p. 243.

7. H. L. Miller and J. E. Sunderland, "Thermal Conductivity of Beef," Food Technology, 17(4), (1963), p. 490.

8. J. C. Harper and A. F. El Sahrigi, "Thermal Conductivities of Gas-Filled Porous Solids," Industrial and Engineering Chemistry Fundamentals, 3, (1964), p. 318.

9. W. M. Massey, Measurement of Thermal Conductivity During Freeze-Drying of Beef, Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1966.

10. A. Shenhav, A New Method for Measuring the Thermal Conductivity of Insulating Materials, Master's Thesis, Northwestern University, Evanston, Illinois, 1962.

11. H. Zierfuss, "An Apparatus for the Rapid Determination of the Heat Conductivity of Poor Conductors," Journal of Scientific Instruments, 40, (1963), p. 69.

12. ASTM Designation C177-45, "Thermal Conductivity of Materials by Means of the Guarded Hot Plate," ASTM Standards, Part 5 ASTM, (1961), p. 953.

13. N. E. Hager, Jr., "Thin-Heater Thermal Conductivity Apparatus," The Review of Scientific Instruments, 31(2), (1960), p. 177.

14. J. Schröder, "A Simple Method of Determining the Thermal Conductivity of Solids," Philips Technical Review, 21(12), (1959-1960), p. 357.

15. W. M. Underwood and R. B. McTaggart, "The Thermal Conductivity of Several Plastics, Measured by an Unsteady State Method," Chemical Engineering Progress Symposium Series, Heat Transfer-Storrs, 56(30), (1960), p. 261.

16. C. M. Pelanne and C. B. Bradley, "A Rapid Heat-Flow Meter Thermal Conductivity Apparatus," Materials Research and Standards, 2, (1962), p. 549.

17. C. O. Chichester, E. M. Mrak, and G. F. Stewart, Advances in Food Research, 13, Academic Press, New York and London, 1964, p. 1.

18. F. K. Lawler, "American Progress in Freeze-Drying," Freeze-Drying of Foodstuffs, Columbine Press, London, 1963, p. 270.

19. E. H. Callow, "Meat Equations," Australian Institute of Refrigeration, 2, (1949), p. 1086.

20. H. L. Miller and J. E. Sunderland, "Investigation into the Mechanism of Freeze-Drying," Final Report, Northwestern University, Evanston, Illinois, Quartermaster Corps Food and Container Institute Contract DA-19-129-QM-1487, (1961).

21. R. A. K. Long, "Some Thermodynamic Properties of Fish and their Effect on the Rate of Freezing," Journal of the Science of Food and Agriculture, 6, (1955), p. 621.

22. M. Jakob, Heat Transfer, 1, Wiley, 1949.